DRIVER LINAC BEAM DYNAMICS

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R&D Category: Driver Beam Dynamics and Simulations

ABSTRACT

The main concept of the RIA driver superconducting (SC) linac was formulated during the ISOL Task Force meeting in August 1999 and includes two strippers for uranium and acceleration of multiple charge state beams [1]. R&D work has been concentrated on two main topics: 1) modification and improvement of the physics design of the driver linac, 2) and development of an end-to-end simulation code. We have completed the development of the computer code TRACK that allows us to track multi-component heavy-ion beams directly from the ECR source to the production targets. The code includes stripper simulation based on Monte-Carlo techniques and complete 3D electromagnetic fields represent all elements of the driver linac. On a standard PC the code can track up to 10^6 particles while on multi-processor version of the TRACK can simulate a million particles through several hundred randomly seeded accelerators. The random seeds simulate transverse alignment errors and variations in RF amplitudes and phases of the accelerating fields. Extensive use of the code allowed us to study many problems related to the design of high-power accelerators. Future studies will be devoted to further optimization of the driver accelerator design, which will eventually result in lower cost of the driver linac providing specified beam parameters.

RECENT PROGRESS

Although the main concept of the driver accelerator has not changed since 1999 [1], a number of significant modifications have been added to the original design. Many of these modifications have been made on the basis of an improved understanding of high-intensity heavy-ion beam dynamics [2-11]. The following beam dynamics features have been successfully studied and implemented into the driver linac design:

- An experimental confirmation of simultaneous acceleration of multiple-charge-state beams.
- Possibility to accept a two charge state heavy-ion beam from the ECR and form extremely low longitudinal emittance in the front end.
- Design of a compact focusing-accelerating lattice which minimizes emittance growth.
- Methods to compensate magnetic or/and electric steering and higher order components of defocusing electric field in SC resonators;
- Several types of parametric resonances which can take place in SC linacs were found and recommended to be avoided.
- Stripper effects on heavy-ion beam parameters.
- The concept of a "beam-loss-free" linac was developed and implies beam halo collimation in designated areas. By proper collimation along the post-stripper

magnetic transport system (MTS), beam losses in the high-energy part of the accelerator can be avoided completely [12].

- Major contributors to the effective emittance growth are identified and they are: a) multiplicity of charge states; b) passage through the stripping foils and c) random errors of rf fields and misalignments of focusing elements.
- Other minor mechanisms of the beam halo formation were found and are discussed in [11-12].
- Design of the beam transport system which is capable to match multiple-charge-state beam to the six-dimensional acceptance of the driver linac sections.
- Advantage of using the lower frequency triple-spoke resonators in the high-energy section to provide larger longitudinal acceptance and substantially reduce probability of beam losses.

We have modified and updated the computer simulation code TRACK [4] which now has the following features:

- Integration of particle trajectories of multi-component ion beams in 6D phase space;
- Electrostatic, magnetostatic and electromagnetic fields of all RIA elements are obtained from 3-dimensional external codes and are used for particle tracking.
- Misalignments and random errors are included. Beam steering procedure is applied to the linac with misaligned components [13].
- Space charge fields of multi-component ion beams are obtained from the solution of the 3D Poisson equation.
- Beam passage through stripping foils and films is included. Particle distribution in 6D phase space obtained from Monte-Carlo transport of heavy ions through the stripper with the code SRIM [14] is incorporated.
- Parallel computing on multiprocessor computer cluster JAZZ at ANL. Simulation of total 10^7 particles through the RIA driver linac in 15 hours has been demonstrated [15].
- Capability of end-to-end simulation of beam dynamics in the RIA driver linac which starts at the exit of the ECR and ends at the production target.

Figure 1 shows beam particle envelopes in the end-to-end simulation of uranium beam in the driver linac. This simulation has been performed for the “baseline” design with 402 SRF cavities including 188 elliptical cell cavities (ECL). The simulation starts with $4 \cdot 10^4$ particles in two charge states 28+ and 29+ of uranium ions from the ECR, five charge states are selected for the further acceleration after the first stripper and four charge states are selected after the second stripper. The multi-harmonic buncher and RFQ provide 80% capture. This particular simulation does not include beam space charge. The LEBT design with space charge effects is being not yet completed. The phase space plots in Fig. 1 show beam at the fragmentation target. Beam is focused to ±0.3 mm in the horizontal plane and ±1.0 mm in the vertical plane.

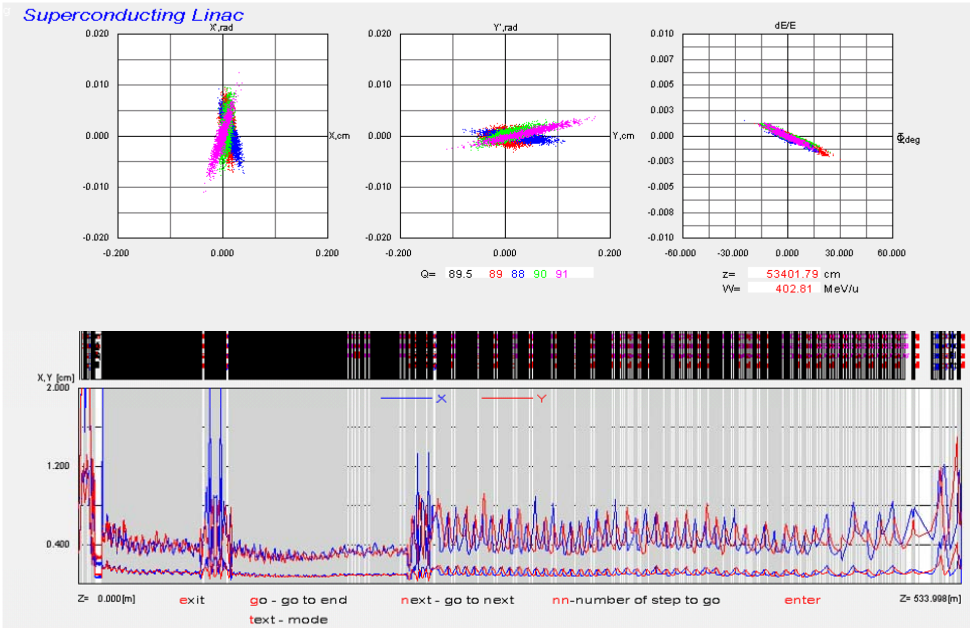

Figure 1: Two-charge-state uranium beam envelopes along the RIA driver linac and switchyard. Transverse and longitudinal phase space plots are shown at the fragmentation target.

BEAM HALO CLEANING

The most recent beam dynamics studies were related to passage of a heavy ion beam through the stripping film or foil which results in a decrease of the average energy due to the ionization losses and both transverse and longitudinal emittance growth due to scattering and energy straggling. The most significant emittance growth and halo formation in the driver linac is associated with the second stripper. There are no experimental data of detailed particle energy and angle distributions after the passage of ~85 MeV/u uranium beam through a stripping foil. We have used the code SRIM [14] for the Monte Carlo simulation of the transport of incident monochromatic beam containing 10^6 uranium ions through a stripping foil. Figure 2 shows the particle distribution in the (α,W) plane, where $\alpha = \sqrt{x'^2 + y'^2}$, and W is the ion energy per nucleon. A strong correlation between the large scattered angles and ion energy is clearly seen from the figure. This correlation suggests a simple way to remove the low-energy halo by the system of collimators along the post-stripper magnetic transport system (MTS). The main collimator is located in a highly dispersive area of the MTS and dumps all unwanted charge states. An additional five collimators along the MTS are designed to clean the beam halo in the transverse phase planes. The transverse acceptance of the MTS with the collimator openings of ± 10 mm is shown in Fig. 3. The acceptance of the MTS with collimators is 45 times larger than beam rms emittance and ~10 times smaller than the acceptance of the high-β section. As shown in the simulations, the collimators clean the beam in the four-dimensional phase space. Because in the driver linac there are no uncontrollable mechanisms for halo formation, beam collimation in the MTS creates the possibility of avoiding any beam losses associated with the beam dynamics.

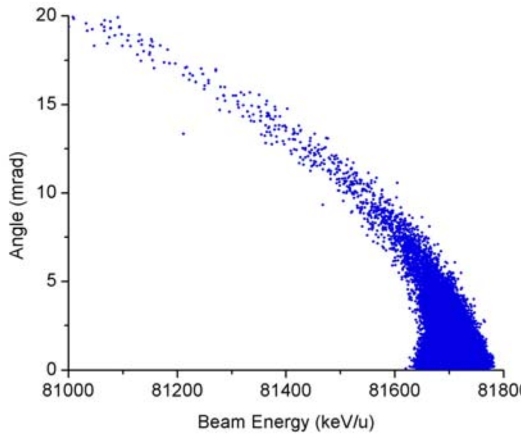

Figure 2. Distribution of uranium ions in the angle-energy plane.

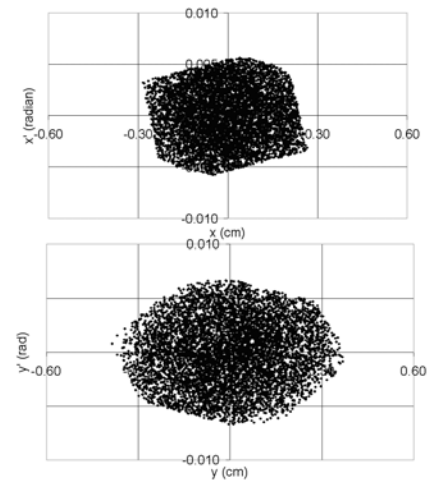

Figure 3. Transverse acceptance of the MTS with collimators.

To avoid beam losses completely, the longitudinal acceptance of the high-β section must accept the full beam emittance, including halo particles. As was mentioned in ref. [16] the longitudinal acceptance can be increased by the factor of four if the triple-spoke resonators operating at 345 MHz are used in the high-β section of the linac. Basic results of the simulations are summarized in Table I. We have assumed ±5% stripping foil thickness fluctuation. Two designs of the high-β section have been studied:

1) elliptical cavity linac (ECL) which is the baseline design for the RIA driver linac and
2) triple-spoke linac (TSL).

Table I. Relative beam losses in high-β section of the driver linac

δW (keV/u)	Rf errors	Beam loss in ECL	Beam loss in TSL
17.6 (SRIM)	±0.5°,	no	no
53	±0.5%	$6 \cdot 10^{-5}$	no
88		$2 \cdot 10^{-4}$	no

If the energy distribution after the stripper is taken from the SRIM code there are no losses in the high-β section for the both linac designs. The TSL is much less sensitive to the energy distribution after the stripper as well as to the stripper thickness fluctuations.

CONCLUSION

We have developed a solid "reference design" of the driver linac. A study of this design by end-to-end simulation using the TRACK code does not show uncontrolled beam losses. The concept of a "beam-loss-free" linac which implies beam halo collimation in designated areas at the post-stripper MTS has been developed recently.

The following work is needed in near future:

1) Future studies will be devoted to further optimization of the driver accelerator design, which will eventually result in lower cost of the driver linac.
2) The following work is currently in progress:

- Comparison of different options of the driver linac.
- Development of specifications to the steering magnets.
- Studies of beam parameters sensitivity to errors/misalignments/strippers.
- Simplification of the post-stripper transport systems.
- Beam collimation, cleaning of 4-dimensional beam emittance, and design of the shielding.

3) Experimental study of particle energy and angle distribution after the stripping of 85 MeV/u uranium. Preliminary data of the beam energy distribution after the stripping foil shows appreciable discrepancy between the measurements and SRIM calculations.
4) Complete the TRACK code manual and distribute among the research groups working in this field.
5) Some modifications of the TRACK version for parallel computing are required.
6) Perform end-to-end simulations of all new options of the driver linac and compare beam quality with the reference design.

REFERENCES

1. K. W. Shepard et al., in the Proc. of the 9th Inter. Workshop on RF Superconductivity, Santa Fe, New Mexico, November 1999, p. 345.
2. P.N. Ostroumov and K. W. Shepard, Phys. Rev. ST Accel. Beams 3, 030101 (2000).
3. P.N. Ostroumov, K. W. Shepard, V.N. Aseev and A.A. Kolomiets, Proc of the 2000 Linac Conf., Monterey, August 2000, SLAC–R-561, p. 202.
4. P. N. Ostroumov and K. W. Shepard, Phys. Rev. ST. Accel. Beams 11, 030101 (2001).
5. P.N. Ostroumov, R.C. Pardo, G.P. Zinkann, K.W. Shepard and J.A. Nolen., Physical Review Letters, 86, N 13, 26 March 2001, p. 2798-2801 (2001).
6. M. Portillo, V.N. Aseev, J.A. Nolen and P.N. Ostroumov, Proc. the 2001 PAC, June 2001, Chicago, IL, p. 3012.
7. P. N. Ostroumov. Phys. Rev. ST. Accel. Beams 5, 030101 (2002).
8. P.N. Ostroumov et al., Phys. Rev. ST Accel. Beams 5, 060101 (2002).
9. A.A. Kolomiets, P.N. Ostroumov, V.N. Aseev and R.C. Pardo. Paper RPAB068 presented at PAC2003.
10. K. W. Shepard, Paper ROPA003 presented at PAC2003.
11. P.N. Ostroumov, Paper WOAB007 presented at PAC2003.
12. P.N. Ostroumov, "Sources of Beam Halo Formation" , Presented at ICFA Advanced Beam Dynamic Workshop Halo'03, May 19 - 23, 2003, Montauk, N.Y. USA.
13. E.S. Lessner and P.N. Ostroumov. Multiple-Charge-State Steering in the RIA Driver Linac. These Proceedings.
14. J.F. Ziegler, J.P. Biersack and U. Littmark, The Stopping and Range of Ions and Solids, Pergamon Press, NY, 1996.
15. B. Mustapha, et al, Large-scale computing simulations for beam dynamics and target modelling. These Proceedings.
16. K. W. Shepard, P. N. Ostroumov, J. R. Delayen, High-Energy Ion Linacs Based on Superconducting Spoke Cavities, Accepted for publication in Phys. Rev. ST. Accel. Beams.